Review of Computer Engineering Research
2025 Vol. 12, No. 2, pp. 48-65
ISSN(e): 2410-9142
ISSN(p): 2412-4281
DOI: 10.18488/76.v12i2.4215

Developing smart tire pressure monitoring system: A performance evaluation of ESP32-C3 with ESP-NOW communication

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Article History
Received: 11 March 2025
Revised: 21 April 2025
Accepted: 2 May 2025
Published: 20 May 2025

Keywords
ESPNOW
Internet of Things
Microcontroller
Tire pressure monitoring system
Tire temperature.

ABSTRACT

This study aims to develop a low-cost and energy-efficient Tire Pressure Monitoring System (TPMS) that provides real-time monitoring of tire pressure and temperature using IoT-based wireless communication. The system was built using the MS5803-14BA sensor, ESP32-C3 microcontroller, and ESP-NOW wireless protocol. Performance was tested through laboratory and real-world scenarios and compared to two commercial TPMS systems (Level A and B). The proposed TPMS achieved 95.91% accuracy, closely aligning with Level A (99.87%) and slightly outperforming Level B (95.35%). It showed the highest temperature sensitivity (10.00%) while maintaining stable pressure readings (6.45%). In contrast, Level B exhibited greater pressure fluctuation (9.68%). The ESP-NOW protocol enabled reliable, low-power data transmission without interference. The developed system delivers high accuracy in detecting tire conditions in real time and demonstrates superior power efficiency and environmental stability, making it a strong alternative to traditional RF-based TPMS solutions. This system can be integrated into smart vehicles or fleet management platforms, enhancing safety through real-time alerts and enabling predictive maintenance. Future enhancements will include broader IoT connectivity, improved calibration, and extended testing in extreme conditions.

Contribution/Originality: This study presents a real-time TPMS prototype using ESP32-C3 and ESP-NOW, offering improved wireless stability over existing systems. Unlike previous works, it emphasizes accurate pressure-temperature monitoring under dynamic conditions and introduces an open-source framework for scalable integration, remote access, and predictive maintenance in IoT-based vehicle monitoring applications.

1. INTRODUCTION

In today's technological development, tire pressure monitoring technology, or TPMS, is increasingly used, especially to support driving safety. However, based on research and data from the National Highway Traffic Safety Administration (NHTSA), about 25% of vehicle accidents in the United States are caused by improper tire pressure [1, 2]. The accident rate due to tire failure can be described in Figure 1. Accidents due to tire failure are also common in Indonesia; out of a total of 226 accidents, 18 cases (85.71% of the total accidents due to vehicle factors) were due to tire failure. Tire failure is an important cause because it can cause a vehicle to lose control, especially when traveling at high speeds on highways [3].

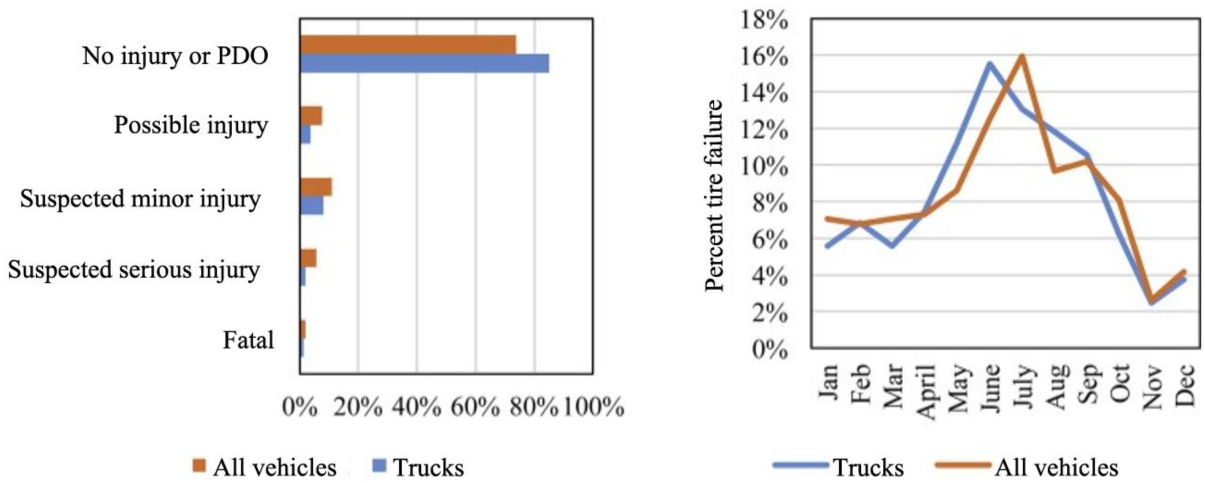

Figure 1. Tire failures by injury severity, speed, month, and truck configuration.

Source: Haq, et al. [1].

TPMS allows drivers to monitor tire pressure in real time, reducing the risk of accidents caused by improper tire pressure. Data from safety organizations show that poorly maintained tires are a significant contributor to traffic accidents. As awareness of safety and efficiency increases, the development of advanced TPMS is becoming increasingly important.

Available TPMS on the market typically use radio frequency (RF)-based communication protocols, such as 433 MHz [4]. Despite their advantages in terms of coverage, these systems have several limitations, such as limited integration capabilities with smart devices and a relatively high cost. Some modern TPMS have adopted Bluetooth connectivity but still face challenges related to data accuracy and reliance on additional devices such as external receivers separate from the vehicle [5].

An effective pressure monitoring system not only focuses on measuring tire pressure but should also include temperature monitoring. High and low temperatures can affect tire performance and overall vehicle safety. Understanding the relationship between temperature changes and tire pressure is critical because tire pressure can vary up to 1 PSI for every 10 degrees Fahrenheit increase in temperature [6]. Therefore, systems that can integrate pressure and temperature sensors into a single unit are of great interest to the automotive industry.

Many conventional TPMS are currently on the market; however, challenges such as signal transmission efficiency and measurement accuracy remain significant issues. The dissipative nature of tires can affect signal efficiency between the TPMS module and the vehicle dashboard [7]. The goal of this research is to develop a specialized TPMS that can monitor not only pressure but also temperature while ensuring improved signal efficiency and reliability. In addition, this research will address the optimal placement of the sensors, as the location of the sensors can greatly affect the accuracy and reliability of the data obtained.

In this study, the MS5808-14BA sensor was used for tire pressure and temperature monitoring. This sensor was selected for its superior ability to provide accurate and stable readings under various operating conditions [8]. By comparing the data obtained from these two parameters, this study will evaluate the effectiveness and accuracy of the system and determine its reliability under specific conditions [9, 10]. In addition, tests will be conducted in various operating scenarios, including extreme temperature changes, to ensure that the proposed system functions effectively in real-world situations. A comprehensive analysis of the data collected will provide valuable insights into the performance of the sensors and their potential applications in advanced tire monitoring systems.

This research aims to make a significant contribution to TPMS technology by overcoming the limitations of existing systems while improving vehicle safety and operational efficiency. Using advanced sensors and innovative installation techniques, the results of this research are expected to provide new insights and become an important reference for the development of TPMS technology in the future.

The following section of this paper outlines the methodology used in this study, followed by the results and analysis, and a discussion of the findings.

2. RESEARCH AND METHODOLOGY

This section describes the research and methodology used, employing a prototyping approach. The methodology consists of several stages: conducting a literature review, designing and building a prototype, creating test scenarios, conducting tests, and analyzing the results.

In developing the TPMS model, key considerations include the selection and integration of pressure and temperature sensors to ensure that the design reflects real-world conditions. The prototype will be made from PLA material. Test scenarios will be used to evaluate system performance under conditions such as high-speed driving and temperature fluctuations. Each test will measure key performance indicators, including signal accuracy and response time.

2.1. Literature Review

In the process of TPMS using pressure sensors, it is very important to carefully define the development stages. In this research, Silalahi et al. [11], TPMS development requires careful planning at every stage. In this research, a TPMS system was developed based on the MPX5500 pressure sensor equipped with transmitter and receiver modules. The system is designed to monitor tire pressure in real-time and provide warnings when the tire pressure is below the safe limit. The prototype model is shown in Figure 2.

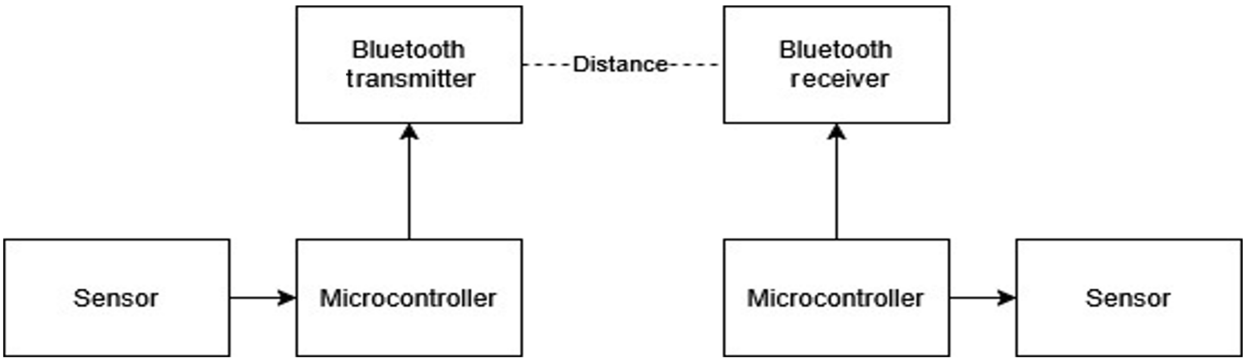

Figure 2. Block diagram prototype monitoring & control TPMS.

Source: Silalahi, et al. [11].

This illustration shows a system that uses wireless communication for data transfer using Bluetooth technology. On the left, sensors collect data that is processed by a microcontroller. The processed data is transmitted wirelessly by a Bluetooth transmitter. Remotely, the data is received by the Bluetooth receiver on the right side of the system. This receiver passes the information to another microcontroller, which drives the LCD screen to visually display the collected data. This setup is an example of a common wireless communication architecture for sensor-based monitoring systems.

In developing the TPMS shown in Figure 2,, the first step is to select appropriate pressure and temperature sensors to detect conditions inside the tire. The data from the sensors are processed by the microcontroller and transmitted wirelessly using a Bluetooth module. At the receiving end, the data is received by the Bluetooth receiver, processed by the microcontroller, and displayed on the LCD screen. This process ensures real-time and accurate monitoring of tire pressure and temperature.

In Figure 2, the system is evaluated and validated to ensure the accuracy of the sensor measurements and the reliability of wireless communication. Evaluation includes testing the sensors at various pressures and temperatures to ensure standardized results. Bluetooth communication validation is performed by measuring the stability of data transmission over various distances and environmental conditions. The results of this phase are used to improve the system design if deficiencies are found, allowing the TPMS system to function optimally and provide reliable information to the user.

Identifying tools and materials to develop the TPMS prototype involves selecting key components such as pressure and temperature sensors, a microcontroller with wireless communication capabilities, a communication module such as Bluetooth or ESP-NOW, and a high-efficiency battery power source. In addition, supporting components such as PCBs for integration, antennas for signal amplification, and software for microcontroller programming are required. The choice of communication protocol depends on the specific requirements of the system, such as low power consumption or wide signal coverage.

After the prototyping phase, field tests are conducted to ensure that the system performs well in real-world conditions. Testing includes simulating in-tire conditions, measuring sensor accuracy, battery life, and wireless communication reliability. Test results are used to iterate the design until the system meets the desired performance standards.

Several studies of various types have been conducted to develop remote tire pressure monitoring to reduce rubber waste from tire wear [12]. In addition, another system uses intelligent tire monitoring using flexible sensors and PVDF (polyvinylidene fluoride) piezoelectric sensors [13]. This research is very possible as a reference or reference to this research. Other research on TPMS through the development of smart tires that harvest their own energy as part of the Internet of Vehicles (IoV) has identified three main sources of mechanical energy for harvesting: gravitational acceleration in the wheels, centrifugal acceleration in the tire inner liner, and tire strain [14]. A new indirect TPMS based on adaptive extended Kalman filtering with unknown input (AEKF-UI) is developed. The system uses the linear relationship between tire stiffness and tire pressure to monitor pressure indirectly through a time-varying parameter estimation algorithm [15]. Focuses on using smart sensors equipped with microprocessors to enable message encryption and authentication. The system replaces the original sensor ID with an anonymized ID to protect the privacy of the vehicle's location, and all messages are encrypted with a key that is dynamically updated after each communication session [16].

Data collection involved using vibration sensors to analyze tire wear patterns at 25%, 50%, 75%, and 100% wear levels. The data was processed using the CatBoost machine learning algorithm, which is capable of classifying wear levels with high accuracy [17]. Her research included analyzing the relationship between tire wear and the level of data transmission security. In other research, a Bluetooth-based compact antenna for TPMS was developed to improve data transmission efficiency and reduce electromagnetic interference in complex tire environments [18]. Figure 3 shows the transmission system of the compact antenna.

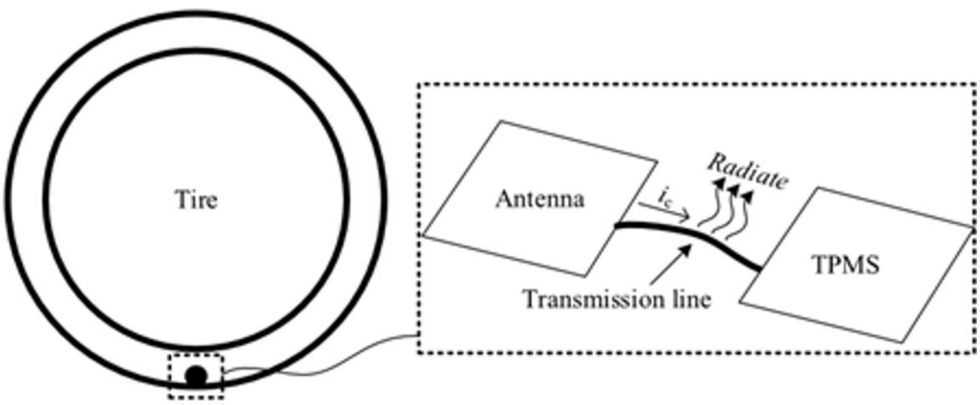

Figure 3. TPMS signal current in the tire environment.

Source: Deng et al. [18].

Figure 3. The antenna is designed to overcome the challenges of the entire electromagnetic environment, such as resonance loss due to metal and dielectric materials, and ensure high data transmission efficiency. This is important to support Bluetooth-based TPMS operations that require energy efficiency and compatibility with modern devices.

Another study focused on Fiber Bragg Grating (FBG)-based fiber optic sensors to monitor key parameters in vehicle tires under real operating conditions. This technology, developed within the OPTYRE project, aims to measure the circumferential strain of tires in real-time, providing insight into contact phenomena between the tire and the road, such as contact trace length, rolling resistance, and residual grip [19]. An overview of the sensor placement can be seen in Figure 4.

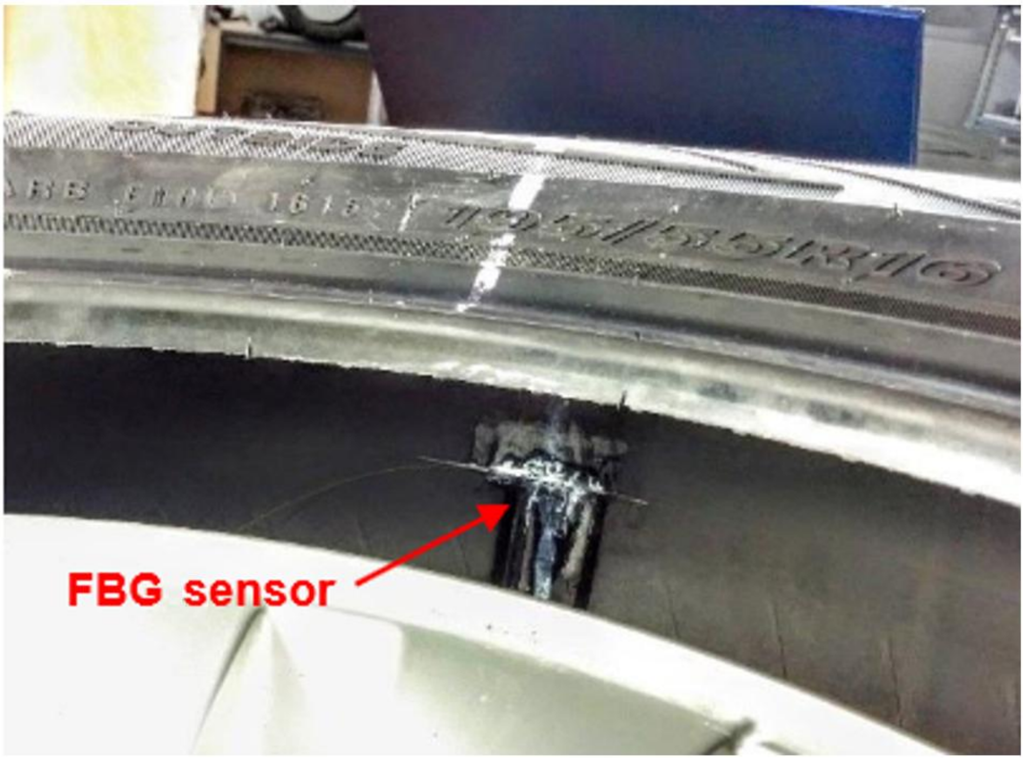

Figure 4. FBG sensor glued inside the tire.

Source: Coppo, et al. [19].

Other research conducted utilizes the deformation of tires in contact with the road [20], with its main components consisting of an elastic steel pipe, a pulling rope, a generator, a protective housing, a rotary cylinder, a planetary gear, and a spiral spring. When the tire is compressed, the elastic steel pipe pulls the rope that rotates the cylinder and shaft, driving the generator to generate electricity. This research discusses the benefits of deformation when the tire is in contact with the surface.

Several techniques in developing IoT-based tools to monitor tire pressure and fuel volume of vehicles in real-time using sensors and NodeMCU microcontrollers that can be monitored directly through the Blynk application [21]. Then another study developed an h-TPMS (hybrid TPMS) system that uses only one pressure sensor but is able to estimate the pressure in all four tires [22]. Feature extraction method and lazy-based classifier for analyzing vibration signals collected under idle, high-speed, normal, and leaky conditions using MEMS accelerometers [23].

Uses a hybrid wavelet-Fourier transform to extract important features from tire vibration signals, which are then analyzed using CNN. This method aims to detect tire eigenfrequencies that correlate with tire pressure, without requiring a direct pressure sensor inside the tire [24]. With its ability to learn and adapt to various road and vehicle conditions, as well as its potential to reduce implementation costs compared to a direct TPMS.

The MS5803-14BA sensor is a pressure sensor that can be implemented in various applications, such as water depth measurement [25], inline pressure measurement [26], soil pore pressure measurement [27], and other applications. The mechanism of this sensor involves a piezoresistive element on a silicon membrane that detects pressure changes [28]. When pressure is applied, the membrane deforms, which changes the resistance of the piezoresistive element. This change is converted into an electrical signal by the sensor's internal circuitry.

The advantages of this sensor make it suitable for applications such as TPMS, water pressure monitoring, and IoT-based systems. One of its main advantages is its extremely small size, making it ideal for applications in confined spaces [29]. The sensor also has a wide pressure measurement range, ranging from 0 to 14 bars, so it can be used for a variety of needs. In addition, the MS5803-14BA is equipped with a built-in 24-bit ADC that enables data readout with high resolution and an accuracy level of ±0.1 mbar. The sensor offers digital communication via I2C and SPI interfaces, which makes integration with modern microcontrollers easy.

Referring to Figure 2, the data transmission system on the TPMS prototype can be implemented using the MS5803-14BA sensor connected to the ESP32-C3 Super Mini microcontroller as the sending unit. The data is then transmitted wirelessly using the ESP-NOW protocol, which enables fast and power-efficient short-range communication between ESP32 devices.

2.2. Design of Tire Pressure Monitoring System

The Block Diagram shown in Figure 5 shows a prototype designed to monitor pressure and temperature. The system uses strategically positioned MS5803-14BA sensors for high-accuracy measurement of pressure and temperature. Then the data obtained from the sensors is sent through the ESP32-C3 as the main microcontroller. The ESP32 plays a dual role as middleware for data processing and a dashboard receiver to display real-time information. The system is able to detect and measure pressure and temperature continuously, store measurement data, and display it through the monitoring dashboard [30].

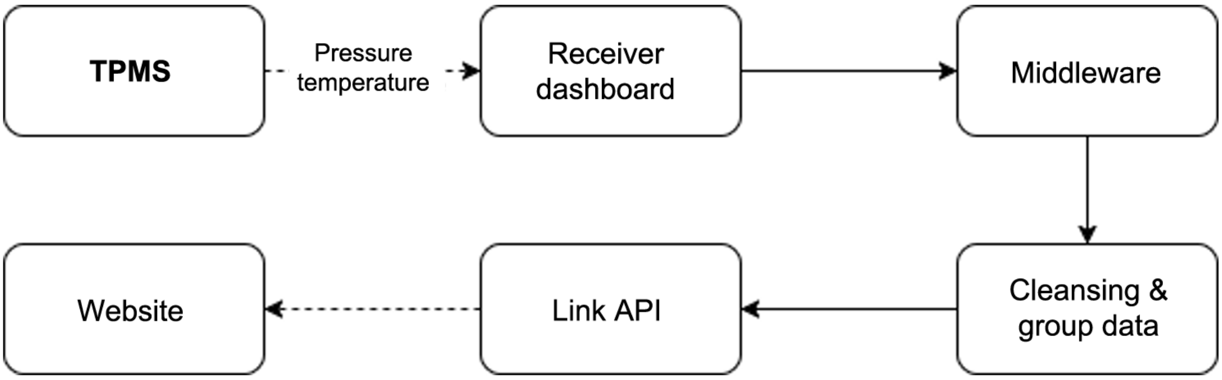

Figure 5. Block diagram of TPMS prototype.

The MS5803-14BA sensor is used to measure the air pressure and temperature inside vehicle tires. With its compact dimensions and high measurement stability, the sensor can be installed in areas that are most exposed to stress due to changes in air pressure during tire movement. The placement of the sensor is designed to protect it from damage due to shock and the extreme environment inside the tire, resulting in consistent and reliable data.

Meanwhile, the module's PLA casing design is precision-printed using a 3D printer to protect the sensor from physical impact and environmental exposure, such as extreme temperatures or humidity. The placement of the sensor in the casing is designed to remain responsive to the air pressure inside the tire without compromising the accuracy of the readings. This system combination enables simultaneous pressure and temperature measurement, providing critical data for real-time tire condition monitoring while minimizing the number of sensor connections to ensure long-term system reliability.

Before testing, the initial values of the MS5803-14BA sensor are calibrated using a digital pressure gauge to ensure the accuracy of the pressure and temperature measurements. The calibration process was performed to determine the analog values corresponding to the pressure (in PSI) and temperature (in °C) produced by the sensor. The calculations are shown in (1) for pressure and (2) for temperature.

$$Pressure = \left(\frac{ADC\ Value}{16{,}777{,}215}\right) \times 20 \quad (1)$$

$$Temp = -40 + \left(\left(\frac{ADC\ Value}{16{,}777{,}215}\right) \times 125\right) \quad (2)$$

The results of the calculations shown in (1) and (2) result in a pressure and temperature calibration process. The pressure calibration process is conducted by measuring the analog value generated by the pressure sensor and converting it into absolute and relative pressure units.

Based on the measurement results, the analog value read from the sensor at 16800000 shows an absolute pressure of 1013.25 mbar. This value indicates that the environmental pressure is at standard atmospheric conditions. The resulting gauge pressure is 0.00 PSI, which indicates that there is no significant pressure difference between the measured pressure and the reference pressure.

The temperature calibration process is performed by connecting the temperature sensor to the system and recording the analog values read at various ambient temperatures. From the measurement results, an analog value of 800,000 correlates with a temperature of 22°C, while values of 850,000 and 900,000 indicate temperatures of 23°C and 24°C, respectively.

This shows that the sensor is capable of detecting temperature changes within a relatively small range, which is expected for environmental condition monitoring applications.

After the calibration stage is complete, the MS5803-14BA sensor is then integrated into the TPMS module according to the design that has been established. This sensor is then connected to the ESP32-C3, which functions as the main microcontroller.

The ESP32-C3 is responsible for reading and processing data from the sensor, as well as sending pressure and temperature information wirelessly using the ESP-NOW protocol. With this implementation, the developed TPMS system can be used for real-time monitoring of vehicle tire conditions and allows data access through Internet of Things (IoT) technology.

Overall, proper placement of the sensors on the TPMS module is critical to optimizing the functionality of the sensors and enhancing their usability. The accurate placement of the MS5803 pressure and temperature sensors in the TPMS case ensures consistent and accurate data readings, resulting in sufficient output for further data processing.

2.3. Flow Chart System

The workflow of the developed TPMS system is described in the diagram in Figure 6, which illustrates the main stages in the process of capturing data from sensors, processing the information, and sending the data to the intended platform.

The diagram shows how the system detects and processes pressure and temperature data and transmits it to the receiving unit before finally sending it to the API for storage or further analysis. With this diagram, the system workflow can be understood more clearly and systematically.

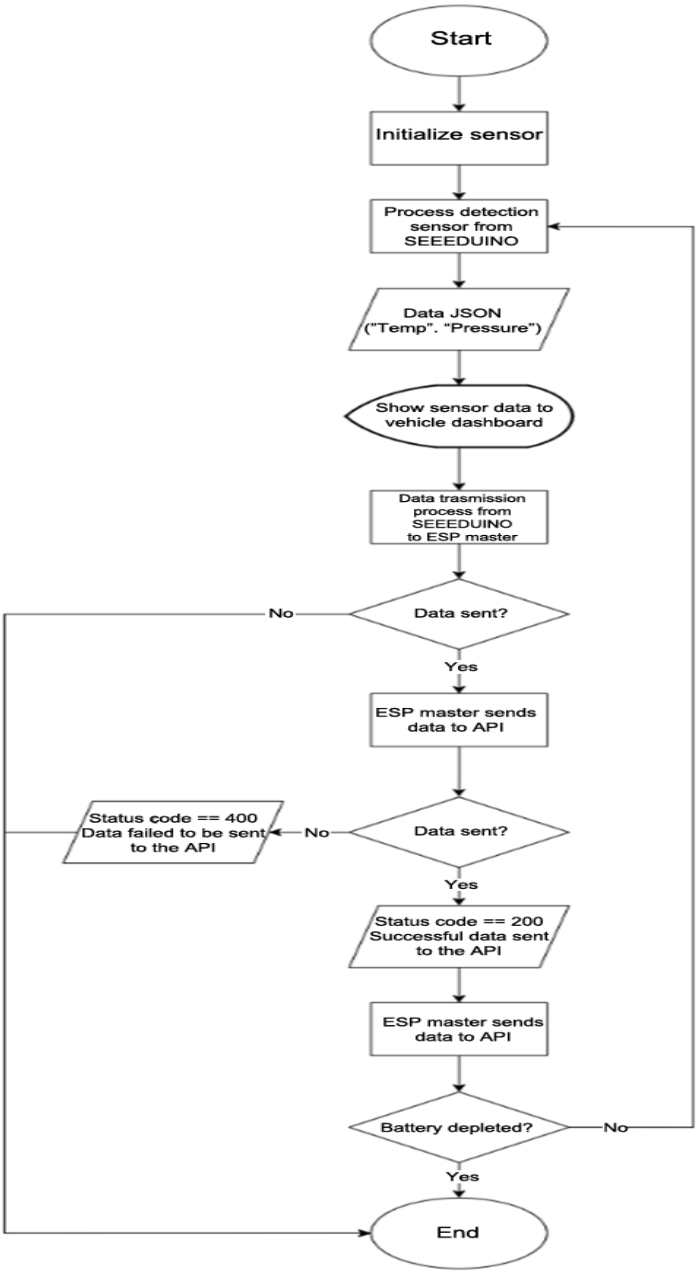

Figure 6. Flowchart of developing TPMS.

The diagram is a visual representation of a sensor monitoring system implemented using ESP Master architecture with API integration. The system applies to a structured and systematic sensor data collection methodology, where the sensor initialization process is a fundamental stage in starting the system's operational cycle.

The JSON (JavaScript Object Notation) implementation is used as a standard format for data serialization, facilitating interoperability and efficiency in information transmission between sensors and dashboards [31]. The data validation mechanism is integrated through a status code system, where code 200 indicates successful data transmission, while code 400 represents a failure in the process of sending data to the API.

This system architecture adopts an iterative approach through a loop mechanism controlled by a time constraint parameter. When the time limit has not been reached, the system automatically initiates a re-reading cycle, ensuring continuity in data acquisition and transmission. This implementation reflects the fundamental principles of real-time monitoring systems, with an emphasis on reliability and consistency in data collection [32].

2.4. Testing Scenario

Several factors were considered in this experimental setup to improve the sensor's ability to accurately measure ambient air pressure [33]. The MS5803-14BA sensor is mounted on a TPMS module designed to mimic the environment inside a tire, as shown in Figure 7. This placement ensures that the sensor can accurately sense pressure and temperature according to the system's requirements.

Figure 7. Sensors and microcontroller housed in a 3D case.

The prototype consists of 3 main components: ESP32-C3, MS5803-14BA, and 2 CR2450 batteries. The 3 components are used to develop the TPMS system that produces hardware and software prototypes that support the basic functions of monitoring vehicle tire pressure and temperature. The system is designed to read pressure and temperature values through the MS5803-14BA sensor [34], process the data with ESP32-C3, and send it via wireless communication. The results are in the form of TPMS prototype hardware, source code, and test results against various work scenarios.

Calibration coding and mapping in this system is done as a calibration method for the sensor by converting the pressure value from mbar to PSI [35]. The goal is to improve the performance of the MS5803-14BA sensor to provide accurate and reliable measurements. By using a formula that can convert absolute pressure and atmospheric pressure values to relative pressure. In (3) and (4), a calculation is presented to calculate the PSI value at relative pressure.

$$P_{relative} = P_{absolute} - P_{atmospher} \quad (3)$$

$$P_{PSI} = P_{relative} \times 0.0145038 \qquad (4)$$

If the relative pressure result is less than 0 (for example, if the absolute pressure is less than atmospheric pressure), the value is set to 0 because negative pressure is not relevant to TPMS applications. After obtaining the relative pressure in mbar, the value is converted to PSI units (Pounds per Square Inch) [36].

To test the initial performance of the proposed TPMS in a controlled environment, the device was first placed in an empty gallon of mineral water. The pressure sensor, microcontroller, and battery were placed in a special protective case designed to withstand shock and changes in air pressure. After ensuring that all components were functioning properly, the gallon was sealed to prevent air leakage during testing. The goal of this step is to simulate confined space conditions that can replicate the environment inside a vehicle tire, but with easier access for system monitoring and refinement.

Air is gradually pumped into the gallon until it reaches a maximum pressure of 15 PSI, while the TPMS continuously monitors the pressure change in real time. The data obtained were compared to an external pressure gauge to evaluate the accuracy of the system. The test also observed whether the signal sent by the TPMS remained stable inside a closed container. If the results are as expected, the next phase of testing can be conducted with scenarios that are closer to real-world conditions, such as installation inside a vehicle tire. The TPMS test in a gallon can be seen in Figure 8.

Figure 8. Pressure-filling trial with digital compressor.

The TPMS prototype is then tested under real pressure to verify the accuracy of the measurements and results. In this test, the sensor, microcontroller, and battery are mounted on a housing that was printed in 3D using PLA material [37]. The prototype TPMS is mounted directly into the vehicle tire, as shown in Figure 8, using the most common TPMS mounting method on the market. The tire is then inflated to simulate actual driving conditions. In this second scenario, the tire is gradually inflated to a pressure of 25 PSI, allowing the system to be tested under higher loads, similar to real-world applications. The TPMS continuously records and transmits pressure data, which is then compared to a calibrated pressure gauge to verify its accuracy. In addition, the stability of the data transmission is monitored to ensure that the signal remains consistent despite the dynamic conditions inside the rotating tire.

In the third scenario, the TPMS prototype was tested in an actual vehicle to evaluate its performance under real-world driving conditions, as seen in Figure 9. The system was installed inside the vehicle's tires, ensuring that the sensors, microcontroller, and battery were securely positioned inside the protective housing. Once properly installed, the tires were inflated to the recommended pressure, and the vehicle was prepared for a test drive around campus.

Figure 9. Installation of TPMS prototype on car alloy wheels.

During the test, the vehicle was driven over a variety of road conditions, including smooth pavement, speed bumps, and inclines, to observe how the TPMS responds to dynamic pressure changes. The system continuously transmits real-time data, which is logged and analyzed to evaluate its accuracy, stability, and reliability on the road. Any differences between the TPMS readings and the reference pressure monitor are recorded for further calibration. This test is an important step in validating the ability of the TPMS to function effectively in everyday driving scenarios. The tire installation is shown in Figure 10.


Figure 10. TPMS was installed and tested on the car.

3. RESULT AND DISCUSSION

3.1. Result

The first scenario in the TPMS prototype test was conducted to evaluate the pressure and temperature sensing performance of the MS5803-14BA sensor in a laboratory environment. This test was conducted using plastic gallons as test media to simulate a closed environment. The gallon is pressurized to 15 PSI using a calibrated digital compressor to ensure that the applied pressure matches the reference value. Sensors are placed inside the gallon to record real-time changes in pressure and temperature. The data obtained were compared with the reference from the compressor to evaluate the accuracy and response of the sensor to pressure changes. The purpose of this test is to ensure that the sensor works properly in the laboratory before being used in the field.

The test results show that the MS5803-14BA sensor is capable of detecting pressure changes with a high degree of accuracy. With an initial pressure of 15 PSI, the sensor recorded an average reading of 14.9 PSI, with a difference of 0.1 PSI from the digital compressor reference. Throughout the test, the pressure variation remained within a range of ±0.1 PSI, indicating the stability of the system under closed environmental conditions. In addition, the sensor successfully recorded the temperature change within the gallon, averaged against the reference thermometer, as described in Table 1.

Table 1. Result testing on mineral gallon.

Actual (PSI)	TPMS pressure (PSI)	TPMS temperature (°C)
11	10.0	22.0
12	11.8	22.1
13	12.0	22.0
14	13.7	22.1
15	14.9	22.0

With actual pressures ranging from 11 to 15 PSI, the TPMS readings ranged from 10.0 to 14.9 PSI. The average difference between the actual pressure and the TPMS pressure is about 0.18 PSI, indicating that the system is fairly accurate. In addition, the temperature detected by the TPMS remained stable at 22.0°C to 22.1°C, indicating that the sensor did not experience significant fluctuations during the test. These results show that the prototype TPMS can measure pressure accurately and consistently in a laboratory environment using a gallon-based test method.

After the testing phase was completed, the results of the measurements on the plastic gallons were analyzed to determine the accuracy, stability, and reliability of the TPMS system. Challenges identified, such as signal transmission interference in a closed environment, were used as a reference for further development.

In the next scenario, tests were conducted comparing Level A and Level B TPMS systems in a second scenario where the TPMS was mounted on a vehicle tire and inflated to a calculated 25 PSI to 30 PSI using a portable compressor. The results show that the accuracy of air pressure readings varies depending on the sensor and data processing algorithm. Factors such as sensor calibration, the reliability of electronic components, and environmental conditions affect this variation. A graphic representation of the research results is shown in Figure 11.

The test results indicate variations in pressure readings among the TPMS systems. The Level A TPMS demonstrated the highest accuracy, with minor deviations such as 25.7 PSI at an actual 26 PSI and 28.1 PSI at 28 PSI, achieving an accuracy rate of 99.87%. The Level B TPMS showed larger discrepancies, particularly reading only 27.0 PSI at an actual 28 PSI, with an accuracy of 95.35%. The proposed TPMS exhibited more consistent readings than Level B but still had small variations, achieving 95.91% accuracy. These differences are influenced by sensor response characteristics, calibration precision, and data processing algorithms within the microcontroller, which affect signal conversion and measurement accuracy.

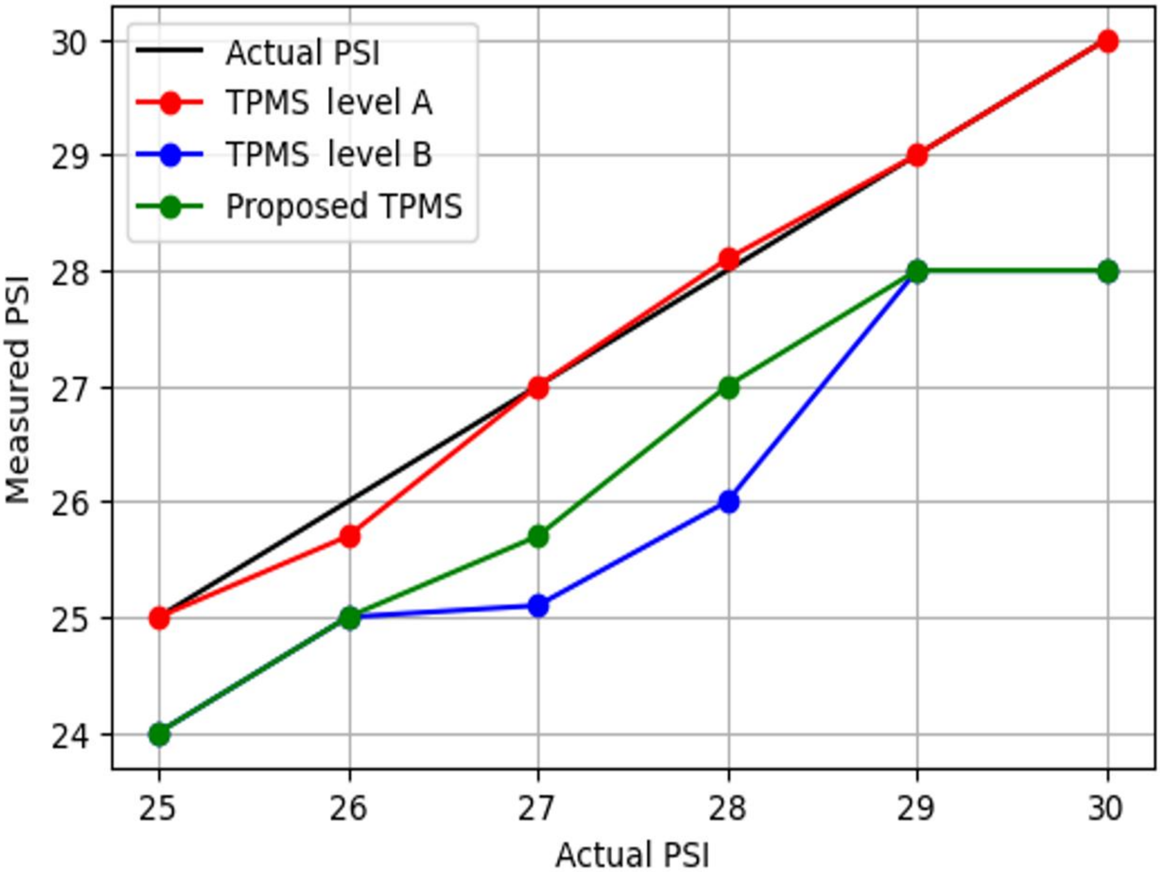

Figure 11. TPMS testing graph visualization.

In the third test scenario, TPMS Level A, Level B and Proposed were installed on three different tires of a vehicle, which was then driven around the campus for approximately 6 minutes. This test was designed to evaluate the performance of each TPMS under real-world driving conditions, including variations in road surface and tire movement. The results are shown in Figure 12.

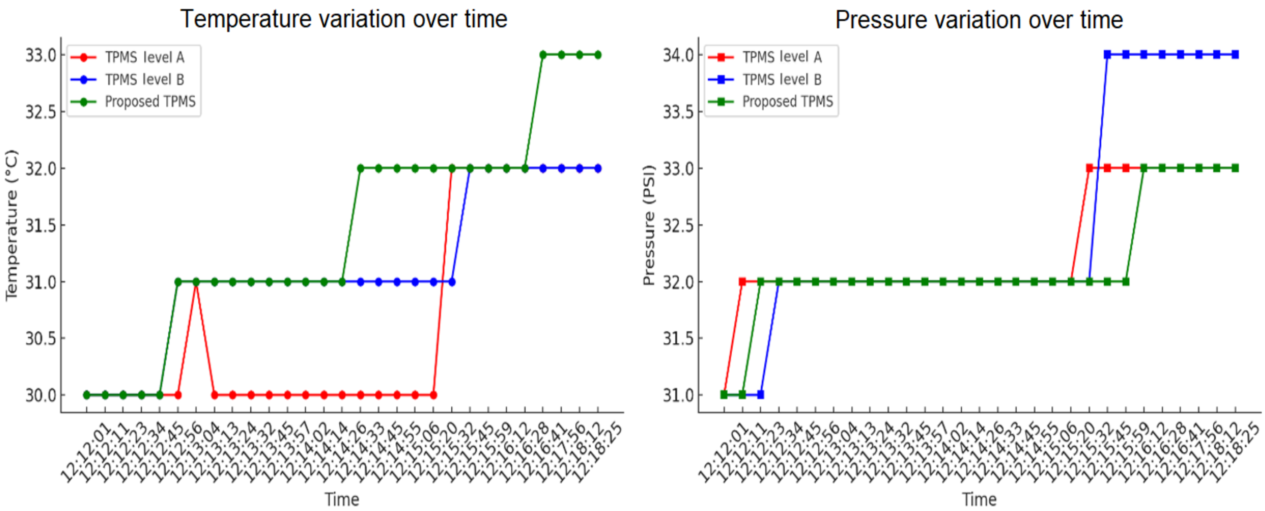

Figure 12. Test results of the 3 TPMS in vehicles.

From the graphical results shown in Figure 12,, the temperature and pressure increase simultaneously over time, which shows a direct correlation. The proposed TPMS shows the highest temperature increase of 10.00%, indicating better sensitivity to temperature changes compared to the Level A and Level B TPMS, which both increase by 6.67%. However, despite the higher temperature sensitivity, the proposed TPMS maintains a consistent pressure increase of 6.45%, just like the Level A TPMS. Meanwhile, the Level B TPMS shows the highest pressure rise of 9.68%, indicating that it is more affected by temperature fluctuations.

These results confirm that temperature significantly influences tire pressure, as described by the ideal gas law. The varying percentage changes among the three systems highlight that different TPMS designs offer different accuracy levels. The proposed TPMS demonstrates better stability in pressure readings, making it more reliable. An optimal TPMS should incorporate temperature compensation to deliver accurate pressure measurements, enhancing vehicle safety and performance.

3.2. Discussion

This research develops a prototype TPMS using MS5803-14BA pressure and temperature sensors. This TPMS system is designed to monitor the air pressure and temperature inside the vehicle tires in real time, with the data transmitted through the ESP32-C3 microcontroller using the ESP-NOW wireless communication protocol. This prototype provides an innovative solution to improve vehicle safety and operational efficiency, particularly in ensuring that tire pressure remains optimal during use.

The system consists of three main components: the MS5803-14BA pressure and temperature sensor, the ESP32-C3 as the main microcontroller, and two CR2450 batteries as power sources. The placement of the sensor is strategically designed inside the tire to ensure stable and consistent data readings under various environmental conditions, such as changes in temperature or pressure as the vehicle moves. The sensor is also protected by 3D-printed PLA-based housing that serves to protect the components from shock, moisture, and exposure to the tire's interior environment.

Before use, the MS5803-14BA sensor is calibrated to ensure measurement accuracy. The calibration process is performed by comparing the analog value (ADC) of the sensor to the actual pressure (PSI) and actual temperature (°C). The test results show that this TPMS system works well in detecting changes in air pressure and temperature. The pressure data sent to the receiver matches the actual conditions, so it can be used as an early indicator in tire pressure monitoring. The system provides a quick response to pressure changes, allowing the driver to take immediate action in the event of a pressure mismatch.

The proposed TPMS has an open-source nature so that it can focus on improving communication stability and power efficiency to ensure optimal performance under various usage conditions. With the API provided, the system is designed to be easily extensible, allowing integration into predictive tire maintenance solutions. The data generated is open source, so it can be used for predictive vehicle maintenance, helping to anticipate potential problems before they occur. While there are slight variations in size, the system maintains open-source data accessibility, allowing for further research and innovation in tire pressure monitoring and safety improvement.

This research effectively established an IoT-based Tire Pressure Monitoring System (TPMS) utilizing the MS5803-14BA sensor, ESP32-C3 microcontroller, and ESP-NOW communication protocol. The test results indicated that the developed system successfully detected tire pressure and temperature in real-time, demonstrating a high level of accuracy. This system demonstrated an accuracy of 95.91%, surpassing Level B's accuracy of 95.35%, yet remaining marginally below Level A, which stands at 99.87%. This study found that temperature directly affects tire pressure, with a 10.00% increase in temperature correlating with stable pressure fluctuations of 6.45%. In contrast, the Level B system exhibited a higher pressure fluctuation of 9.68%. This system's primary benefit lies in its implementation of ESP-NOW as a wireless communication protocol, demonstrating superior power efficiency and reduced disruption compared to traditional RF-based TPMS. Consequently, the established system is capable of delivering timely alerts regarding variations in tire pressure with greater efficiency.

This study presents distinct differences and advantages when compared to prior research in the area of TPMS. Fechtner et al. [5] developed a TPMS utilizing Bluetooth 5 technology to enhance the communication efficiency between sensors and monitoring systems. While Bluetooth provides a reliable connection and is compatible with contemporary devices, it exhibits limitations in terms of higher power consumption when compared to ESP-NOW utilized in this analysis. Consequently, the system created in this study demonstrates enhanced energy efficiency, rendering it more appropriate for prolonged use without necessitating regular battery replacements.

A study conducted by Lee et al. [15] introduced an indirect Tire Pressure Monitoring System (iTPMS) utilizing the Adaptive Extended Kalman Filtering (AEKF-UI) method, which enables the estimation of tire pressure without the need for direct sensors within the tire. This method is contingent upon mathematical modeling of the vehicle, which frequently results in diminished accuracy under diverse road conditions. This study presents a system that employs direct sensors, resulting in enhanced accuracy and reliability of data across diverse road conditions. Additionally, research conducted by Márton et al. [24] employed Convolutional Neural Networks (CNN) to examine tire vibrations and assess pressure through resonance frequency estimation. This approach minimizes reliance on physical pressure sensors; however, it has constraints in rapidly forecasting tire pressure due to the necessity for more intricate data processing. This study demonstrates that the TPMS systems utilizing ESP32-C3 and ESP-NOW facilitate quicker real-time monitoring, as pressure and temperature data are transmitted and analyzed directly, eliminating the necessity for supplementary AI-based processing. A study conducted by Briantoro [33] introduced an IoT-based tire pressure monitoring system utilizing NodeMCU and the Blynk App to provide real-time pressure data visualization. Nonetheless, the study employs a Wi-Fi-based communication protocol, which presents certain limitations in scenarios characterized by weak signals or unstable networks. This study employs ESP-NOW, facilitating direct communication between devices independent of a Wi-Fi network or internet connection, thereby enhancing efficiency in constrained network environments. This comparison indicates that the research provides a more practical and efficient contribution through the integration of direct pressure sensors, low-power communication, and real-time monitoring capabilities, all while operating independently of an internet connection. This study's results present several important implications for automotive technology and vehicle monitoring systems. Real-time tire pressure monitoring enhances safety by providing drivers with immediate awareness of any drop in pressure or rise in temperature. This allows for timely preventive actions to be taken, reducing the risk of tire failure and the potential for accidents. This system provides cost efficiency, as the implementation of ESP-NOW demonstrates greater power efficiency compared to conventional RF-based TPMS technology. The incorporation of cost-effective sensors facilitates the large-scale deployment of this system, applicable to both private vehicles and commercial vehicle fleets. One more benefit is its capacity for integration with IoT platforms, allowing this system to facilitate remote monitoring through mobile devices or cloud computing. This feature enables the TPMS system to facilitate vehicle fleet management and supports predictive maintenance through the analysis of long-term tire pressure data.

The findings of this study indicate strong performance; however, it is essential to acknowledge certain limitations that warrant consideration. The test remains confined to vehicles operating at low to medium speeds, failing to assess its performance under extreme conditions, including potholes, severe weather, or significant temperature fluctuations in snowy regions. This study exclusively utilized the MS5803-14BA sensor and the ESP32-C3 microcontroller, which limits the analysis to these specific components and does not allow for a comparison with potentially more efficient alternatives in terms of sensors or microcontrollers. When evaluating communication options, it is evident that while ESP-NOW demonstrates power efficiency and low interference, its signal range remains inferior to that of technologies like LoRa or NB-IoT, which could be more appropriate for larger vehicle applications. The findings and constraints indicate multiple avenues for future research that warrant exploration. Optimizing power and communication efficiency involves exploring alternative communication protocols like LoRa, Zigbee, or NB-IoT to enhance signal range and minimize power consumption. This system can be enhanced through the application of machine learning algorithms, which can analyze patterns of pressure and temperature changes over time to predict the likelihood of tire failure. To enhance system reliability under real-world conditions, it is essential to conduct testing in extreme environments, including high temperatures found in desert regions and low temperatures experienced in snowy areas. A further potential advancement involves integration with intelligent vehicle systems like ADAS (Advanced Driver Assistance Systems) and the Internet of Vehicles (IoV). This would enable vehicles to autonomously modify speed or issue audio alerts in response to any abnormal fluctuations in tire pressure. In conclusion, additional research could be conducted to compare different types of pressure sensors, including the MPX5700, BMP388, and Fiber Bragg Grating (FBG)-based sensors, to determine which sensor demonstrates superior accuracy and efficiency for TPMS.

4. CONCLUSION

This research successfully developed a TPMS prototype using the MS5803-14BA sensor, ESP32-C3 microcontroller, and ESP-NOW communication. The system effectively measures tire pressure and temperature in real time, ensuring reliable monitoring with a fast response to pressure changes. Compared to commercial TPMS, the developed system demonstrated competitive accuracy, with Level A achieving 99.87%, the proposed TPMS 95.91%, and Level B 95.35%. The study also confirmed the strong correlation between temperature and pressure, with the proposed TPMS experiencing the highest temperature rise of 10.00% but maintaining a stable pressure rise of 6.45%, while Level B had the highest pressure fluctuation of 9.68%, indicating greater sensitivity to environmental changes. The developed TPMS offers advantages over traditional RF-based TPMS by integrating with smart devices, improving cost efficiency, and reducing signal interference. The system's real-time data transmission allows drivers to take immediate corrective action, enhancing vehicle safety and tire longevity. Future improvements will focus on optimizing power consumption, refining wireless communications for stability, and integrating IoT capabilities for remote monitoring. With these enhancements, this TPMS has great potential for real-world applications, contributing to safer and more efficient driving. Further development could focus on improving power efficiency to extend battery life, as well as optimizing wireless communication to ensure data transmission stability under various conditions. In addition, integration with IoT technology can enable remote pressure monitoring via mobile devices or the cloud. With the results achieved, this TPMS prototype has the potential to be further developed into a more reliable and efficient TPMS. Further optimization is expected to improve the system's performance so that it can be widely used in various types of vehicles.

Funding: This research is supported by PPM of Telkom University, Bandung Technopark (Telkom University), and PT. Transtrack, Indonesia (Grant number: KWR4.039/BTP01/BTP/2024).
Institutional Review Board Statement: Not applicable.
Transparency: The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.
Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.

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